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Inhomogeneous superconducting states and umklapp processes in ferromagnet/superconductor nanostructures

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Abstract

We derive a new boundary-value problem (BVP) for the ferromagnetic metal/superconductor (FM/S) nanostructures, where superconductivity is a superposition of the BCS pairing with zero total momentum in the S layers and the Fulde–Ferrell–Larkin–Ovchinnikov (FFLO) pairing with nonzero 3D coherent momentum **k** in the FM layers. It is shown that the processes of mutual transformation between BCS and FFLO pairs at the FM/S boundary are the *umklapp processes* during which coherent pair momentum **k** becomes confined in the FM layer. We originally investigate the interplay between the BCS and 3D FFLO states in the pure FM/S bilayers. This competition leads to a partial compensation of the exchange field paramagnetic effect.

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1. Introduction

In recent years, there is a pronounced interest in unconventional superconductivity with electronic correlations different from the usual BCS pairing with zero total momentum. One such example is the Fulde–Ferrell–Larkin–Ovchinnikov (FFLO) type pairing with a nonzero momentum of pairs, which may be realized in the layered ferromagnetic metal/superconductor (FM/S) structures (see review [1] and references therein). The competition of superconducting and magnetic states in the layered FM/S structures leads to a pronounced non-monotonous dependence of the critical temperature T_c on the FM layers thickness d_f. The existing theories of the proximity effect [1] connect the nature of non-monotonic behavior of $T_c(d_f)$ with vibrations of the Cooper pairs flux at the FM/S boundaries, which arise due to one-dimensional (1D) oscillations of the pair amplitude across the FM layers. However, these theories predict multiple oscillations of $T_c(d_f)$, whereas only one local maximum (or minimum) in the experiments with real 3D multilayers Fe/V or Gd/Nb is observed. The reason is that the former 1D theories [1] neglect by spatial changes of pair amplitude along the FM/S boundary. Below, we will show that the 3D states have the higher T_c and right for realization rather than the old 1D states.

2. Boundary-value problem (BVP) for FM/S bilayer

Let us consider the planar contact between the FM layer ($-\infty<z<0$) and the S layer ($0<z<\infty$). The critical temperature T_c of inhomogeneous superconductor is defined by the self-consistency equation [2] for the order parameter $\Delta(\mathbf{r})$

$$\Delta(\mathbf{r}) = 2\lambda(z)\pi T \mathrm{Re}\sum_{\omega>0} F(\mathbf{r},\omega), \tag{1}$$

where $F(\mathbf{r},\omega) = F(\mathbf{r},\mathbf{r},\omega)$ is the one-point anomalous Gor'kov function; $\lambda(z>0)=\lambda_s$ and $\lambda(z<0)=\lambda_f$ are the parameters of the electron–electron interaction. In the

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